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RELIABILITY OPERATIONS

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BASIC PRINCIPLES, METHODS, AND OBJECTIVES OF RELIABILITY OPERATIONS

H. Gross

ABSTRACT: Description of a number of theoretical and experimental research methods associated with engineering reliability. A general outline of the basic concepts of reliability operations is presented, followed by a discussion of the various problems that may be successfully attacked by these methods.

1. Introduction: The Concept of Reliability and its Origin

For each and every technological product, there is a set of certain quantitatively distinct characteristics which define its suitability with respect to the intended use. The totality of these characteristic values is described by the generally accepted concept of "Quality." One widely accepted definition reads [1]: /369*

Quality is that property of a product which permits it to meet satisfactorily the demands made upon it by the use for which it is intended.

Quality characteristics in this narrowly-defined sense thus have a momentary character; they permit quantitative data for those geometric or physical parameters which are essential to the product's application, and they apply always to a particular moment in time which may either be in the present or in the past.

In contrast, the generally accepted concept of "quality" tacitly implies a certain expectation of the behavior of a given product in the future. The consumer who purchases a product, or the entrepreneur, who plans an investment, or even a government agency, which plans an undertaking of national scope such as a research project or defense measures, all have a legitimate interest in as realistic as possible a prognosis for the life of a given product. Such predictions are part of the scope of reliability work which therefore is closely tied to conventional effort at maintaining quality. Thus, the concept can roughly be defined as follows: reliability is the maintenance of quality over a period of time. These simple postulations indicate that efforts at maintaining quality and the work of reliability are closely intertwined, but on the other hand, one cannot state the quality is a concept that is subordinate to reliability.

*Numbers in the margin indicate pagination in the foreign text.

One can also state that reliability as a technical discipline is not at all a new invention but, under different names, has played a role from the early days of technology as an independent component of engineering efforts. In man's desire to solve related problems, systematic methods were introduced early into engineering endeavors, such as strength tests, material and fabrication quality controls, as well as methods for the computation of failure rates. What is new in the development of this discipline in recent years is the transition from pure statistics to applied probability theory. In this sense, the first precise definition for the concept of "technological reliability" was formulated:

Reliability is the probability that a given production unit will not fail within a defined period of time and under given operational and environmental conditions.

However, this definition has the disadvantage that it is formulated too specifically and does not provide for a clear separation between the general concept of reliability and its quantitative definition. In practice, the probability of extended life is as well suited to the description of reliability as, for example, a failure rate or, in specific cases, a mean time between failures (MTBF). Consequently, a somewhat more general definition was subsequently selected [1].

Reliability is the ability of a production unit to satisfy those demands, defined by the intended application, which are made of their properties for a given period of time.

This definition thus establishes a qualitative framework for the concept of reliability whose quantitative definition is affected by a series of characteristic quantities such as failure probability, failure rate, etc. These characteristic magnitudes are of equal weight and can be introduced interchangeably.

The reason for the urgency in dealing with problems of reliability in recent years was the pressure for the development of ever more complex apparatus designed to deal with problems which held ever greater risks for national prestige or the security of human life and the concomitant ever increasing probability of failure. Moreover, some very real economic considerations were involved. For example, investigations in the United States showed that annual costs for operational maintenance of military electronic equipment constitute a cost ranging from 60 to 1,000 percent of the original purchase price [2]. The connection between these costs and the properties of reliability of a given system is clearly evident: unreliable systems must, to perform a given task, be provided in redundant quantities and, in addition, must be constantly maintained: thus, initial acquisition and maintenance costs for the case of reliability $R = 0$, would range from $1/R$ to infinity. Conversely, efforts to increase reliability during the development phase result in costs which, for the hypothetical case $R = 1$, also rise asymptotically toward infinity. Thus, the total costs of a project, which include development, acquisition, and maintenance costs, would result in the curves appearing in Fig. 1. /370

Without going into further detail, such a sober analysis of costs directly leads to the intensification of efforts toward increasing reliability.

To name a few dates and names, it should be noted that in 1943, R. Lusser and E. Pieruschka were the first to combine the known product law of probability with the problem

of the survival chances of technical equipment. It was recognized that the survival chances exponentially decrease with increased complexity, i. e., with the growing number of functioning individual components. Well known are the difficulties experienced by the United States during the Korean War which were based to a considerable extent on technical shortcomings and defects of aircraft which resulted in serious deficiencies in the operational readiness and combat effectiveness of the Air Force.

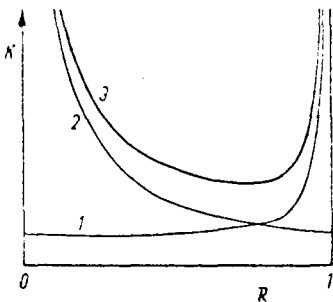


Figure 1. Sample of the Flow of Total Cost of a System in Dependence on its Reliability. 1) Curve of Development Costs; 2) Curve of Acquisition and Maintenance Costs; 3) Curve of Total Costs.

As a result of these negative experiences, the United States during the mid-50's introduced systematic efforts toward increasing reliability in the development of military hardware, primarily in the area of aviation and space. This involvement with problems of reliability was adopted also in Germany where at present a number of specialized groups are engaged in reliability work. Among these are the following:

- a) The "Reliability" Committee of the Nachrichtentechnische Gesellschaft (NTG) and
- b) The "Reliability and Quality Control" Committee of the VDI-Fachgruppe "Luftfahrt und Raumfahrttechnik"

In addition, orientation and thinking in terms of reliability is gaining ground in government agencies, business firms, and institutions of higher learning.

2. Aims of Reliability Work

The principal aims of reliability during the development of a technical product can be described by the following key terms [3]:

- Determination of optimal quantitative reliability requirements for the total system and derivation of reliability requirements for system components.
- Discussion and evaluation of configurations proposed during the course of development with relation to meeting of reliability requirements.
- Evaluation or proof of the state of reliability that has been achieved.

While development proper concerns itself with the technical realization of required functions and with the selection of the optimal design configuration with respect to the fulfillment of the required function, weight, performance, or other characteristic parameters, it is the purpose of reliability work to make sure that the finally selected configuration will, in operation, possess a sufficiently low failure probability. This kind of effort must obviously be mounted not at the stage at which a final design has been completed but, based on time and cost considerations, there must be a constant exchange

of information between the development and the reliability efforts. Thus, it is imperative that reliability be considered at the earliest stages of planning and development.

The proof of reliability constitutes an expansion of proof of technical operational capability of the product under development at completion of development; it should indicate that the required function, under the environmental and operational conditions specified, is assured for a certain period of time. An attempt to provide an experimental proof of reliability generally fails because of the large effort required; in its place, under certain conditions, a semitheoretical procedure may be used in which appropriate evaluation is made of certain data obtained in functional testing. This indicates that reliability must be considered in intermediate testing and evaluation.

An additional task of reliability is the collection, preparation, and evaluation of data. All quantitative reliability data have probability characteristics and are, therefore, statistically measurable. The large quantity of data necessary for suitable statistical evaluation is generally obtainable only at advanced stages of development. Hence it is necessary, for example, during the performance of analyses, to refer to earlier experiences with comparable components or groups of components.

The methods which can be employed to solve the tasks enumerated, can be named as follows:

- Theoretical methods which essentially include causal examination and which permit the derivation of quantitative reliability values by means of theoretical computations.
- Experimental methods which essentially include life tests and tests under simulated operation conditions.
- Coordinative and organizational methods which essentially include the specification, planning, control, and coordination of all reliability efforts and checks performed during the course of a development process.

The following paragraphs will discuss in detail certain procedural rules and suggested solutions for the three categories of methods above.

3. Theoretical Methods

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3.1 Basic Assumptions

Like any system which is composed of a large number of individual elements, a complex technical system is dependent upon a variety of statistically independent factors which, in their totality, determine the behavior of the system. Their interaction is subject to statistical laws and experience has shown that, occasionally, this may result in failure of the system. This phenomenon constitutes a basic characteristic of system behavior and is of such paramount importance that an effort to control it appears justified. Hence the following can be stated:

- The work of technical reliability encompasses the study of the behavior of technical systems, specifically with a particular class of events which can be described as failures.
- Any event that constitutes an unacceptable deviation from specific requirements can be looked upon as a failure.
- Quantitatively, a deviation from specific requirements is the difference between actual and specified performance of a variable.

The variable is a measurable characteristic which serves to obtain the quantitative differentiation of objects or states.

A failure, in the sense defined above, may be a clearly determined, predictable event (predictable in terms of time), or it can be stochastic, i. e., not predictable in terms of time.

In the former case, its occurrence can generally be prevented through suitable preventive measures without too much difficulty. Unfortunately, in the case of complex system, failures of the unpredictable variety are far more frequent.

Such events cannot always be prevented by suitable preventive measures. However, one can attempt to find a way to control these with the aid of a quantitative model of system behavior. For this purpose, as in other disciplines of the natural sciences, one makes a phenomenological postulation which, initially is selected linearly and which corresponds to the known model of spontaneous radioactive disintegration. The postulation is that, for a given collective of like objects, the fraction of the indeterminate failures, per unit time, per time interval, is always proportional to the volume of the balance of the collective:

$$\frac{dN(t)}{dt} = -\lambda N(t).$$

A relative change, i. e., the expression

$$\frac{dN(t)}{dt} \frac{1}{N(t)} = -\lambda,$$

is designated as the rate, in this case, the failure rate. The failure rate frequently, particularly in the case of complex systems, may be assumed to be constant in terms of time, but need not be. For inconstant failure rates, equation

$$\frac{dN(t)}{dt} \frac{1}{N(t)} = -\lambda(t)$$

is applicable, with the solution,

$$N(\tau) = N_0 \exp \left[- \int_0^\tau \lambda(t) dt \right].$$

Here, M_0 is the number of objects in the collective present at time $\tau = 0$.

Reference magnitude $N(\tau)/N_0$ corresponds to survival probability $R(\tau)$ of one element of the collective up to a point in time τ and thus, is a direct measure of its reliability. As regards failure rate λ , its magnitude, whether or not it is constant in time, is obviously also affected by the existing conditions such as vibrations, changes in environmental temperature, electrical loads, etc., to which the element, equipment, or system is subject during the period of time under discussion. Hence, we obtain

$$R(\tau) = \exp \left[- \int_0^{\tau} \lambda_r(t) dt \right].$$

To avoid misunderstandings, the following note is in order:

The "time" parameter in the reliability function is not a running "time" coordinate which would tend to vary the reliability of the given object; it is instead the duration of a time interval to which the survival probability is referenced. The numerical value obtained from the above reliability equation,

$$R(\tau) = X\%,$$

therefore may not be interpreted to mean that the object under examination after τ hours will have a reliability of $X\%$. That is, if up to this point there have been no failures, the reliability, that is, the probability that the equipment's function will be fulfilled, remains 100%. More correctly stated: starting from a specific point in time at which the equipment was still operable, the probability that no failure will occur within a specific time interval τ is $X\%$.

If the above reliability equation is looked upon as a mathematical model for the actual behavior of a given object during its life, a number of differing assumptions must be made of the flow of failure rates for specific cases. For example, cases of failure due specifically to wear are characterized by failure rates that increase with time. The failure density function, that is, the frequency of failures, referenced to initial state N_0 , is in this case the well-known bell curve shown in Fig. 2. In the case of complex technical configurations one frequently encounters,

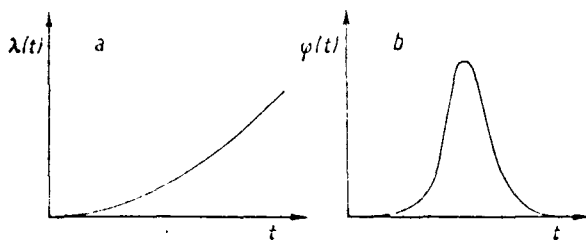


Figure 2. Basic Course of; a) Failure Rate; b) Failure Density Function Due to Wear.

in more or less well delineated form, a failure rate which is aptly referred to as the "bathtub curve" (Fig. 3). At the beginning of the life cycle, this failure rate shows a tendency to decrease; this is the area of the so called early failures or, as one is apt to say, the infant mortality, which may be caused by defects in manufacture which make themselves felt early during operation. This is then followed by an area of nearly constant failure rate, i.e., the area of stochastically undeterminable occasions of failure; the constancy of the failure rate is the more accurate the greater the number of components and the more mixed the age of the different components. Toward the end of the system's life, the failure rate

curve again begins to climb since, at that point equipment wear begins to make itself felt.

Theoretical reliability analyses generally assume failure rates that are constant in terms of time, i.e., only the middle portion of the bathtub curve is of concern.

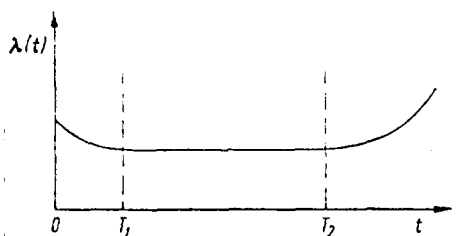


Figure 3. Course of Failure Rate of Complex Systems. $0 \leq t \leq T_1$: Area of Early Failures;
 $T_1 \leq t \leq T_2$: Area of Occasional Failures;
 $t \geq T_2$: Area of Failures Due to Wear.

This simplification is justified when early failures can be eliminated through suitable breaking-in procedures and failures due to wear can be avoided through appropriate preventive maintenance procedures. The reliability function can then be simplified to read

$$R(\tau) = e^{-\lambda \tau}$$

and thus produces an exponentially declining survival curve. This exponential survival distribution has the property that its median value μ , i.e., the average value of the times at which failures occur, is equal to the reciprocal of the failure rate:

$$\mu = \frac{1}{\lambda} = T.$$

This magnitude, T , which has a time dimension, is called mean time between failures (MTBF) of the given object or system. Most unnecessarily, this concept gave rise to numerous misunderstandings because it was applied -- incorrectly -- also, in cases of non-exponential distributions, for which it is not at all valid, and also because it was sometimes given the totally wrong meaning of "failure-proof duration of operation." Actually, upon expiration of the MTBF, the survival probability has been set at $1/e$ (36.8%), i.e., at this point in time, on the average, almost two-thirds of the original system have experienced failure. In the case of non-exponential distributions, for which the MTBF concept is inapplicable, one has lately occasionally substituted a so-called "MTBF equivalent" which is defined by the relationship

$T' = - \frac{1}{\ln R(t=1h)}$ which is equal to the average value of an exponentially decreasing quasi-distribution curve, defined by the two points $R(0) = 1$ and $R(1)$ of the actual survival curve (Fig. 4).

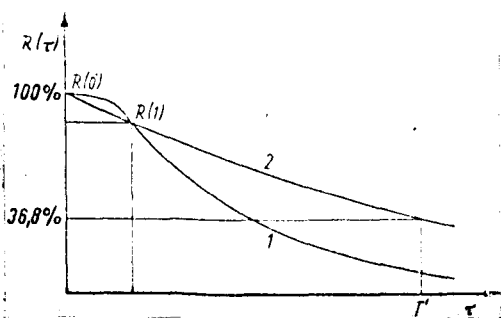


Figure 4. On the Definition of the "MTBF Equivalent." 1) Actual Survival Distribution $R(\mu)$;
 2) Exponential Curve Through $R(0)$ and $R(1)$.

At this point a word on failure rates λ is in order. A number of publications are available which compile empirically obtained data on these.

These data are based, in part, on serial tests performed by manufacturers or users and, in part, on operational experience [4].

However, such data are not generally reliable and require constant checking and correction. The precision of results of a theoretical reliability analysis is limited.

3.2 Weighting Characteristics and Failure Criteria¹

The performance of a theoretical reliability analysis begins with the establishment of a suitable weighing scale in the form of a set of general weighing characteristics which define the reliability properties of the object under observation. Then, this general weighing scale must be adapted to the specific given conditions of the individual case in which system-specific failure criteria are referenced. These are derived from the specific technical requirements made of the system or of its components and define quantitatively the limits up to which these requirements can be considered as having been met. Some of the parameters used particularly with reference to aircraft, but generally applicable are:

a) Freedom from Maintenance

This is the probability that, for a given period of time and for given operational and environmental conditions, a given component or equipment will not require maintenance.

Failures, in the sense of this parameter, are all events which result in the need for maintenance; thus, this applies to the failure of any components which becomes evident through unacceptable deviations from specific standards and which can be corrected by means of repairs, and when they do not impair the function of the whole system.

b) Operational Reliability

This is the probability that, within a given period of operation of the whole system, no failures will occur in the equipment which will either impair or disrupt the accomplishment of the given task.

Only specific failure criteria can be cited which may differ with different operational conditions. Determination of failure criteria is arrived at with the aid of equipment specifications and pertinent economic, technological, and tactical system requirements.

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c) Operational Reliability

This term implies the probability that, during the given operational duration of the system, for example, flight hours of an aircraft, no equipment failures will occur which will endanger the system or its operating personnel. Failure criteria with respect to operational reliability are governed by the same ground rules that apply to operational reliability. A basis for determination of failure criteria is found in equipment specifications as well as in certain specific anthropotechnical safety requirements.

¹Based on unpublished data of the author.

3.3 Mathematical Models

In the course of the theoretical reliability analysis, a mathematical model must now be developed which would describe the behavior of the given system with respect to a specific evaluation characteristic, a specific point in time, and certain defined conditions. This model must satisfy a number of basic requirements such as:

- All available empirical data must be mathematically processed in the model.
- The model must reflect the behavior of the system with respect to specific evaluation characteristics with a citable statistical reliability.
- It must be applicable to any system and evaluation criteria.
- The basic principle and mathematical evaluation of the model should be as clear as possible and should permit use of analog and digital computers.

The construction of a mathematical model must always be based on the concrete failure possibilities that are peculiar to a specific equipment. These failure criteria thus form the principle of selection on the basis of which the critical failures or combinations of failures of components can be separated from the total of all failure possibilities.

The mathematical models most commonly used are based on the application of Boolean algebra or on the classical Markoff methods.

3.3.1 Mathematical Models Based on Boolean Algebra

Use of the procedures and terminology of quantitative algebra permits the derivation of a relationship for every evaluation characteristic between the behavior of a system identified by the two alternate states "failed" and "not failed" and the possibilities of the states of its components. If the individual events are independent of one another, then the thus obtained "system equation" will contain only the elementary quantitative-algebra link operations of the formation of an average and the formation of sums of events. In this case, a simple graphic representation of the system equation is possible in the form of a so-called "logic diagram" in which every event A_j occurring within the equation is symbolized by an element $\boxed{A_j}$; the formation of an average is represented by a logical series arrangement and the formation of a sum is represented by a parallel arrangement of the pertinent elements. In this manner, the weak points in the system representation are immediately recognized. A mutual dependence of individual events must be expressed by complex computations. Graphic representation in the form of a logic diagram is not possible in this case.

The formal assignment of occurrence probabilities to all individual events results in the transformation of the system equation into the reliability equation for the system.

a) Operational Freedom

The mathematical model with reference to the characteristic value of operational freedom, is obtained in the following manner: First, all operational paths a_i of the

system are determined. An operational path is a chain of conditions which, if met simultaneously, permit the system to be fully operational. The condition can be of the form: component A_j operates within specific parameters. The condition for the situation in which no repairs to the system are required, is obtained through the formation of the quantitative algebra average for all operational paths:

$$\bar{f} = \Pi * a_i.$$

For the complementary event "repair needed" there follows, from the duality principle of quantitative algebra,

$$\bar{f} = \Sigma * \bar{a}_i.$$

The probability relation for this mathematical model yields the following equation for the determination of operational freedom

$$p(\bar{f}) = p(\Sigma * \bar{a}_i).$$

b) Operation Reliability

With respect to the characteristic value of operational reliability, the mathematical model can be derived in a manner similar to that discussed above. The condition for the state in which no mission - impairing failures will occur is obtained through formation of the quantitative algebra sum of all operational paths:

$$r = \Sigma * a_i.$$

For the complementary event "mission impairment" there follows, from the duality principle,

$$\bar{r} = \Pi * \bar{a}_i.$$

The probability relation for this mathematical model yields the following equation or determination of operational reliability:

$$p(\bar{r}) = p(\Pi * \bar{a}_i).$$

c) Operational Assurance

The mathematical model to describe operational assurance differs from the model for operational reliability only in the structure of operational paths which reflect only those critical conditions relating to operational assurance.

3.3.2 Mathematical Models Based on the Markoff Methods

Another approach, used with increasing frequency to obtain mathematical models depends on the setting up of so-called state equations based on the classical Markoff methods [5]. The states of an equipment are characterized by the totality of the states of the individual components which make up the equipment for which, in the simplified case, only the

alternatives "failed" - "not failed" are differentiated. For the mathematical treatment it must be assumed that all such states of the equipment are differentiable and mutually exclusive so that the equipment, at any point in time, finds itself in one specific state only. In this case, given a redundancy circuit of two identical individual elements, the following states can be defined:

- Both elements operating.
- One element has failed (No. 1 or No. 2).
- Both elements have failed;

The mathematical treatment here leads generally to a system of simultaneous linear differential equations and can be graphically represented by a state diagram. The probability that, within a period of time $(t, t + h)$, a precise transition will take place from one state into a subsequent state, is $\lambda b + O(b)$ (terms of a higher order in h); the transition rate can always be derived from the failure rates of the individual elements.

For the simple case discussed, the status diagram shown in Fig. 5 is obtained.

If the probability that the equipment, at t , will be in state N , is designated as $P_N(t)$, the following system of differential equations is obtained:

$$\begin{aligned} P_0(t+h) &= P_0(t) [1 - 2\lambda h - O(h)], \\ P_1(t+h) &= P_0(t) [2\lambda h + O(h)] + \\ &\quad + P_1(t) [1 - \lambda h - O(h)], \\ P_2(t+h) &= P_1(t) [\lambda h + O(h)] + P_2(t). \end{aligned}$$

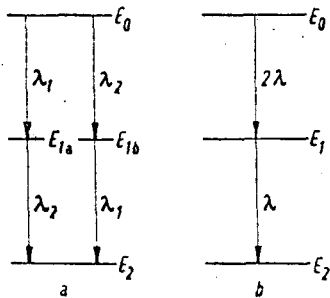


Figure 5. Status Diagram for a Redundant System Consisting of Two Individual Components. a) General Case; b) Special Case for $\lambda_1 = \lambda_2 = \lambda$, $E_{1a} = E_{1b} = E_1$.

For the case $B \rightarrow 0$, we obtain

$$\begin{aligned} P_0'(t) &= -2\lambda P_0(t), \\ P_1'(t) &= 2\lambda P_0(t) - \lambda P_1(t), \\ P_2'(t) &= \lambda P_1(t). \end{aligned}$$

The initial conditions are

$$P_0(0) = 1, \quad P_1(0) = 0, \quad P_2(0) = 0.$$

The simple system is solved and we obtain,

$$\begin{aligned} P_0(t) &= e^{-2\lambda t}, \\ P_1(t) &= 2\lambda t e^{-2\lambda t}, \\ P_2(t) &= 1 - 2\lambda t e^{-2\lambda t} + e^{-2\lambda t}; \end{aligned}$$

Hence,

$$\sum P_i(t) = 1.$$

Complex systems can be evaluated with the aid of analog or digital computers.

The mathematical models constructed on this basis for the characteristic values of operational freedom, operational reliability, and operational assurance of an equipment differ primarily in that it is important at which state of the equipment the failure criteria are being met. In the case of operational freedom, this is the case at state 1; the appropriate state diagram in this case ends at that level. However, when one speaks of operational reliability, state 1 under certain circumstances may only be an intermediate stage and may not mean that equipment failure in the sense of the pertinent failure criteria is imminent.

3.4 Declaratory Value of Reliability Analyses

Analytical reliability analyses are an important aid in the development and evaluation of technical products. Beginning in the early developmental states, such analyses provide quantitative values for reliability characteristics of a given product as well as criteria for intended control of the development. Frequently, during the development stage, only analytically obtained reliability data can be had, particularly when there are reasons why direct experimental measurements of reliability through a series of systematic operational and environmental tests are not possible due to overriding financial or other considerations.

It should be noted that the reliability of analytically obtained quantitative reliability characteristics is limited by the inaccuracy of the numerical input data used. Therefore, it is necessary that, during the course of development, new information concerning these input data must be processed immediately so that the reliability of prediction can be increased. But even in that case, the results of the reliability analysis reflect not the actual state observed during operation since, by definition, they describe only the "inherent" reliability of a design and are based on the assumption of ideal fabrication, handling, and maintenance conditions; thus, they require supplementary data from additional investigations.

The value of a reliability analysis, however, depends primarily not on the quantitative reliability computation, but on the possibility that, through systematic examination, knowledge of the behavior and functional condition of complex systems will be gained, structural defects will be uncovered which otherwise could be found only with difficulty, and a way will be found for effective improvements.

4. Experimental Methods [3]

Proof of the fact that quantitative reliability requirements are met can be obtained, on the one hand, through appropriate evaluation of theoretical reliability analyses, and, on the other, through direct experimental testing. But quantitative evaluation of theoretical reliability analyses is in turn tied to a knowledge of a series of input data which generally are obtainable only empirically. These include, in particular, reliability data about components dependent, in turn on environmental and functional conditions that apply /375 to the individual operational phases, as well as on the behavior parameters of an equipment -- after failure of certain components has occurred -- factors which are important for the construction of mathematical models.

The following can be stated with regard to direct experimental testing of reliability requirements:

Reliability is a probability and thus cannot be measured directly by experiment, but can be measured only statistically. To obtain support of reliability data, experiments may be utilized which permit observation of failure frequency under certain conditions and which allow certain conclusions to be drawn after appropriate statistical test methods have been applied. The inaccuracies inherent in such a procedure require the perfection of an experimentally achieved reliability prognosis by means of the simultaneous declaration of the applicable statistical assurance and the appropriate range of reliability. Assurance and reliability range depend on the test methods employed, the scope of spot checks performed, or the number of defects observed.

In general, to obtain proof of quantitative reliability requirements, the equipment must be tested over the entire period of operational duration under simulated environmental conditions. Time consuming tests based on increased operational or environmental loads and extrapolation of test results to conditions of normal load can not be satisfactory in general, but can conceivably apply only to well defined individual cases. A basic condition for this is the existence of sufficiently accurate information on exponential failure distribution [6, 7].

The experimental proof of the fact that quantitative reliability requirements have been met thus can be obtained only at relatively high cost in time and money. However, if it is determined that equipments already in operation do not have a level of reliability that meets the minimum specified requirements, design changes at that stage, designed to increase reliability, will turn out to be even more costly. For this reason it is recommended that, in spite of the financial burden, a test program designed to prove reliability be initiated prior to the start of mass production. The predicted reliability obtained from this type of test must be weighed against the risk of wrong decisions and the additional loss in time and money that could result from unfavorable decision.

A program of testing which could yield the necessary data during the course of equipment development, should contain the following procedures (developed by H. J. Keller in unpublished papers for the Boelkow Enterprises):

1. Measures for the determination of environmental conditions

Experimental measurements of environment which extend to mechanical and climatic conditions are possible only at advanced stages of development; initially, one must rely on experience data obtained for comparable equipments.

2. Developmental tests

These include in particular tests of developmental prototypes under simulated environmental conditions, life tests of components for the purpose of determining failure rates, including short term tests under intensified environmental conditions, as well as failure follow-up tests in which the failure of individual components is simulated to determine its effect on operation.

3. Qualification tests

These serve to prove that the equipment under development has achieved development objectives and meets the requirements; these tests proceed from individual

components to tests of the whole equipment. Since, during such tests which are performed under aggravated environmental conditions, damage of the equipment under test is not easily avoided, the equipment should not be placed in operation after completion of the qualification tests.

4. Test on delivery

These tests furnish proof that the equipment under test corresponds to the qualification prototype and are performed under reduced environmental conditions to avoid damage to the tested equipment; such tests are generally required prior to delivery of equipment.

5. Coordinative and Organizational Methods [2]

Reliability is no performance parameter in the general sense, it is rather the result of a growth process which is affected by the interaction of a variety of factors during the planning, development, and application of a complex system. To control this process, it is imperative that a comprehensive reliability program be followed with respect to large scale projects. Moreover, one must emphasize not only the technical side of the problem **but one must also pay attention to the many human factors that might affect reliability.** Thus, coordinative and organizational activity in reliability work becomes significant.

The basic elements of a reliability program are:

1. Specification of optimal quantitative reliability requirements for the total system, subsystems, equipments, component groups, and individual components

The point of departure is always the overall system whose technical specifications determine the framework for the required system reliability. Quantitative requirements are later derived from economic analyses and operational studies. Consideration of reliability solely as an optimization parameter is erroneous; the magnitude of greatest importance to the user is the effectiveness of the system as a measure of the probability that a well defined task will actually be carried out by the system. Obviously, **this is a combination magnitude** which includes, in addition to operational reliability and the primary performance parameters, the usability of the system, in other words, the probability that, at a certain point in time, the system will be available for operation. Availability, for its part, is affected by maintainability, i. e., by the probability that a system failure can be removed in a given period of time. The determination of reliability objectives leads to a variation problem in which all basic parameters must be so defined that a specific system effectiveness is achieved at minimum cost. / 376

The next step is the distribution of the total reliability objective over the subsystems and equipments. Given N subsystems, we require

$$\prod_{i=1}^N P_i \geq P_{\text{reliability}}$$

The simplest way to meet this requirement would be, for all P_i , to meet the condition

$$P_i \geq \sqrt[N]{P_{\text{ges.}}}$$

However, this would be unrealistic since the reliability that can be achieved at a given state-of-the-art is a function of the complexity of the subsystem in question. This fact must be considered during the distribution of reliabilities. Thus it is necessary and possible to determine an optimal set of values P_i with due regard to complexity and reliability of already available comparable subsystems.

2. Measures to achieve fulfillment of specified requirements

Included here are applications of suitable theoretical methods, performance of experimental tests of equipments component groups, and components, the training and information of all personnel involved in the project, as well as the establishment of specifications for outside performance which, on the one hand, determine quantitative reliability requirements and, on the other, set the guidelines for the fulfillment of these requirements and for suitable documentation, thus assuring that reliability efforts of subcontractors are coordinated.

All these measures aid in the continuous testing of the state of reliability for the overall system, to determine problem areas and improvement priorities or reliability work.

3. Proof that specific requirements have been met

Such proof can be obtained by theoretical reliability analyses within the framework of qualification tests. Primarily, this would determine the state of reliability at the point of equipment delivery. Experience has shown that, on delivery to the user, systems initially show a considerably lower reliability than those which have had the benefit of inherent reliability testing or prototypes. The reasons for this are based on the transition to operational status and the basically different environmental conditions which then apply. Thus, mass production is subject to conditions quite different from those that pertain to the construction of a prototype; moreover, service and maintenance personnel of the user is at a different technical training level than manufacturer personnel. These and other factors affect operational reliability in a generally negative sense and can be overcome only through evaluation and interpretation of failures and complaints. Thus, a suitable data collection system, jointly with the required technical reporting system, can contribute to an increase in the reliability of a system. In addition, intensive efforts toward improvement of maintainability will increase total availability of a system.

CONCLUSIONS

The significance of technical reliability as a system parameter is primarily based on the fact that it offers a possibility for the description of complex technical systems in the quantitative sense, that it can be controlled through suitable means and that predictions can be made with respect to its future behavior. This property related the reliability concept to the state magnitude of phenomenological thermodynamics, such as

entropy or enthalpy, and the fact that this relationship is not a random one, is based on the statistical behavior methods of the equipments under observation. Based on this view, efforts at reliability resemble the significance of application of thermodynamic methods for the control of processes in the field of industrial engineering.

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